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SPACECRAFT CHARGING EFFECTS ON SATELLITES FOLLOWING STARFISH EVENT

RE-78-2044-057

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COMPUTER SCIENCES CORPORATION

UNDER

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CONTENTS

1. INTRODUCTION

The purpose of this effort is to review spacecraft performance immediately before and after the STARFISH high-altitude nuclear test to determine whether the artificial electron environment produced by the nuclear burst may have caused any discernible spacecraft (S/C) charging effects either through satellite telemetry or through data channels of on-board experiments.

1.1 BACKGROUND

It is well known (Refs. 1-3) that the artificial electron environment produced by the STARFISH nuclear explosion caused problems on numerous satellites and was responsible for the early demise of at least four satellites. At the time of these tests, the principal adverse effect of the electron environment on the spacecraft was thought to be due to long-term ionization effects in semiconductor devices, particularly the exposed solar cells. It is now becoming increasingly clear (Ref. 4) that an electron environment can also produce adverse effects on satellites by charging dielectrics to levels at which spontaneous discharges can occur. Spontaneous discharges associated with charging from the natural electron environment have been blamed for the failure of at least one satellite (Ref. 5) and anomalous operations of many others (Ref. 6). Thus, it is possible that some of the unexplained malfunctions or anomalies after the STARFISH test were, in fact, produced by electron discharges. The possibility of such occurrences is explored further in this report.

1.2 APPROACH

The approach to this effort is summarized below.

1. Review possible charging effects (Section 2).
2. Identify satellites in orbit prior to and after bursts; determine if any satellite projects reported unexplained malfunctions, and review reported causes of satellite malfunctions (Section 3).

3. Determine electron environments at each satellite before and after the burst (Section 4).
4. Determine if the artificial electron environment produced by the burst could have produced charging effects (Section 5).
5. Review satellite performance to determine if any anomalous operation or satellite failure was consistent with that which might be caused by spacecraft charging effects (Section 6).

2. REVIEW OF SPACECRAFT CHARGING EFFECTS

2.1 BACKGROUND

Spacecraft charging caused by both natural and artificial environments has been the subject of much recent research (Refs. 7-8). The primary emphasis has been on the low-energy (1-20 keV) portion of the natural environment. However, it has been pointed out that the high-energy portion of both the natural and artificial environments may also produce substantial charging effects (Refs. 9-11).

Emphasis has been placed on the low-energy portion of the environment because the natural low-energy electron fluxes are orders of magnitude higher than natural fluxes at higher energies (50 keV to several MeV). The lower-energy electrons are stopped on the outside of the structure and are capable of producing discharges on the external portion of the spacecraft. However, the higher-energy electrons, although fewer in number, are able to penetrate the relatively thin spacecraft skin and deposit in dielectrics within the spacecraft. Thus, the high-energy portion of the electron environment may produce distinct charging effects of concern.

The primary differences between charging and discharging produced by the high- and low-energy electrons are:

1. Charging by the lower flux of high-energy electrons requires more time to reach the same field levels than is required for the higher flux of low-energy electrons.
2. The high-energy electron charging and resultant discharges can occur within the spacecraft closer to cables and wires leading directly to electronics (or perhaps within cable dielectrics).
3. The electron energy and, therefore, the potentials to which the high-energy electron can charge dielectrics are significantly higher than for the low-energy electrons.

2.2 SIMPLIFIED CHARGING MODELS

The electron environment can cause the spacecraft to charge up as an entity, or can cause differential charging by depositing the charge in dielectric (or isolated metallic) structures. Charging of the spacecraft as an entity is not likely to cause any discharge effects, and therefore, only differential charging is considered further.

Discharges can result from differential charging of two isolated conductors or of a dielectric material. The primary difference between the two types of discharges is that, in the case of the metal, virtually all charge on one surface can flow to the other after initiation of the discharge, whereas in the case of the dielectric, it is unlikely that all stored charge in an entire dielectric sheet would discharge at one time.

The discharges resulting from a charged dielectric can occur in two distinctly different ways, as illustrated in Figure 1. Charge can accumulate at or near the surface of the dielectric and can flash over to the substrate, as indicated in Figure 1-a. Alternatively, charge near the surface and/or within the bulk can discharge through the dielectric to the substrate, as indicated in Figure 1-b. It is not clear that the magnitudes of currents induced by the one type of discharge will be any different from the other, but the discharge across the surface can generally occur at a lower field level.

The understanding of discharges and the analytical models describing these processes are not yet well developed. A highly simplified model describing the charge and the discharge is as follows (Ref. 11). A flux of electrons J_{inc} is indicated as a dielectric sheet mounted on a conducting substrate. A fraction of the flux Δf is deposited in the dielectric such that the surface charge density σ at any time and after exposure is

$$\sigma = \Delta f \int_0^t J_{inc} \, dt \; . \tag{1}$$

In the absence of points or edges, the resulting electric field is approximately

$$E = \frac{\sigma}{\varepsilon} \; . \tag{2}$$

The dielectric proceeds to charge either until the dielectric discharge threshold is reached or until equilibrium is established in which the charge

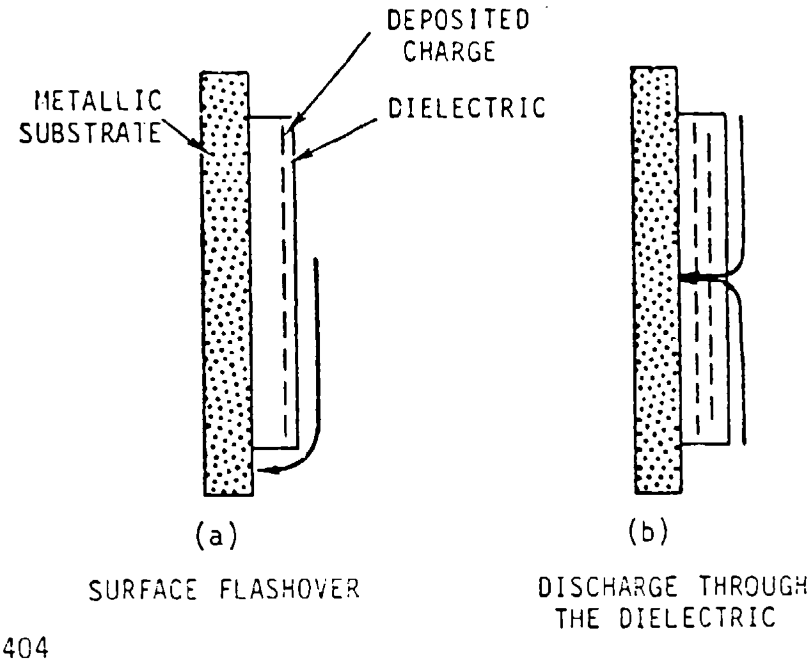


Figure 1. Surface and bulk discharges

leaks off at the same rate it is deposited. In the first case, charge accumulates until the discharge threshold is reached, at which point the surface charge density for a planar geometry is

$$\sigma_B = \varepsilon E_B \ , \tag{3}$$

where E_B is the discharge field threshold. Bulk breakdown thresholds for typical dielectrics are in the range 10^7 to 10^8 V/m, while discharges along the surface generally occur at the lower field values. Surface discharges across 10 mils of typical spacecraft dielectrics have been reported for surface potentials of 10 kV, corresponding to an average normal electric field prior to breakdown on the order of 2×10^7 V/m. Local electric fields at corners or other irregularities, where the surface breakdown is likely to be initiated, will be higher.

The maximum amount of charge involved in the discharge is $Q = \sigma_B A$, where A is the area discharged, a quantity which is by no means known. The peak current in the discharge is on the order of

$$I_D = \frac{Q}{\Delta t} \ , \tag{4}$$

where Δt is the discharge pulse width. The current in the discharge is thought to be significantly greater than the current induced in nearby structures and cables. Presently it is thought that the current induced into a structure some distance from the discharge is on the order of (Ref. 12)

$$I_S \approx \frac{d}{R} I_D , \qquad (5)$$

where d is the effective spacing between the charge layer and the ground plane prior to breakdown (on the order of the dielectric thickness) and R is the dimension of the structure. For a constant electron flux J_{inc}, the time at which discharge occurs is

$$t = \frac{\sigma_B}{\Delta f \, J_{inc}} . \qquad (6)$$

After a discharge, charge again accumulates and subsequent discharges can occur, with the period indicated by the above expression. Of course, the amount of surface charge density released in each discharge may be less than σ_B, in which case the magnitude of the discharge is less, as is the time between discharges.

The second possibility is that equilibrium is reached prior to discharge such that the charge leaks out of the dielectric at the same rate it accumulates. At this point, the electric field is said to be saturated with a value

$$E_{sat} = \frac{\Delta f \, J_{inc}}{\sigma} , \qquad (7)$$

where σ is the conductivity of the dielectric. The conductivity consists of at least two terms — an ambient term σ_0 and a radiation-induced term $\Delta\sigma$ produced by the electron radiation. The radiation-induced conductivity term is generally thought to be proportional to the electron flux in the dielectric

$$\Delta\sigma = \alpha f J_{inc} , \qquad (8)$$

where f is the average fraction of the incident current in the dielectric and α is a proportionality factor relating conductivity to current. For sufficiently high electron fluxes, the radiation-induced conductivity dominates and the saturation field is independent of electron current:

$$E_{sat} = \frac{\Delta f \ J_{inc}}{\alpha \ f \ J_{inc}} = \frac{\Delta f}{\alpha f} \ . \tag{9}$$

The time to reach this type of situation is inversely proportional to the electron flux.

Numerical examples for selected expressions given above are presented in Section 5 for the natural and artificial electron environments.

3. SATELLITES

Between 1958 and 1962, there were a total of nine high-altitude tests which produced artificial radiation belts that persisted for some time. A summary of the tests, dates, locations, and estimates of artificial electron intensities is shown in Table 1 (Ref. 13). The L value of a burst refers to the magnetic field line on which the burst was located. The L value of a particular magnetic field line is the distance of the magnetic field line from approximately the center of the earth* at the equator, measured in units of earth radii.

It is evident that the STARFISH event produced the most intense electron environment by several orders of magnitude. Thus, investigation of possible spacecraft charging problems is directed at those in orbit just before and just after July 9, 1962. A list of all free-world satellites with unclassified payloads known to be operational in earth orbit on July 9, 1962, and/or within the six months immediately after July 9 was compiled from the TRW Space Log (Ref. 14). The list is shown in Table 2, along with launch dates. The active life of each satellite is summarized below. The information on these satellites was obtained from literature listed in the bibliography.

3.1 INJUN 1

Name:	INJUN 1
Active life:	June 29, 1961, to December 1962
Apogee:	1020 km
Perigee:	860 km
Inclination:	67°
Period:	104 min

INJUN 1 was the first of a series of spacecraft designed and built by the University of Iowa for the study of natural and artificial trapped

*Actually, from the center of an equivalent depth producing the magnetic field line.

Table 1. Artificial Radiation Belts, 1958-1962

Designation	Date of Burst	Altitude (km)	Nominal Explosive Yield (TNT Equiv.)	Maximum Omnidirectional Intensity at t=0 $[(cm^2\text{-}sec)^{-1}]$	L Value of Burst	Apparent Mean Lifetime (Approx.)
Teak	August 1, 1958	$\sim$75	10 MT	10^3	1.1	Few days
Orange	August 12, 1958	$\sim$45	10 MT	10^3	1.1	Few days
Argus 1	August 27, 1958	$\sim$200	1.4 kT	10^5	1.7	3 weeks
Argus 2	August 30, 1958	$\sim$250	1.4 kT	10^5	2.1	3 weeks
Argus 3	September 6, 1958	$\gtrsim$480	1.4 kT	10^6	2.0	1 month
Starfish	July 9, 1962	$\sim$400	1.4 MT	10^9	1.12	1.5 years
U.S.S.R. 1	October 22, 1962	Unknown	Submegaton	10^7	1.9	1 month
U.S.S.R. 2	October 28, 1962	Unknown	Submegaton	10^7	2.0	1 month
U.S.S.R. 3	November 1, 1962	Unknown	Megaton	10^7	1.8	1 month

Table 2. Satellites in Orbit Shortly Before and After the STARFISH Event

Satellite	Launch Date	Date of Failure
INJUN 1	June 29, 1961	December 1962
TRANSIT 4B/TRAAC	November 15, 1961	August 1962
OSO 1	March 7, 1962	August 6, 1963
ARIEL	April 26, 1962	November 1962
TIROS 5	June 19, 1962	
STARFISH EVENT	JULY 9, 1962	
TELSTAR 1	July 10, 1962	February 21, 1963
ALOUETTE	September 29, 1962	Operational in 1971
EXPLORER 14	October 2, 1962	October 8, 1963
STARRAD	October 26, 1962	January 18, 1963
EXPLORER 15	October 27, 1962	February 9, 1963
ANNA 1B	October 31, 1962	
INJUN 3	December 13, 1962	November 3, 1963
RELAY 1	December 13, 1962	February 1965
EXPLORER 16	December 16, 1962	August 1963
TRANSIT 5A	December 18, 1962	December 19, 1962

radiation belts, aurorae, airglow, and other geophysical phenomena. INJUN 1 was launched simultaneously with TRANSIT 4A and GREB 3. TRANSIT 4A successfully separated from INJUN 1, but GREB 3 did not. INJUN 1 was designed to be magnetically aligned. However, due to the presence of GREB 3 (which blocked the view of the photometer), it was impossible to keep the satellite constantly oriented on the terrestrial magnetic field throughout an orbit.

INJUN 1 is a 55-pound cylindrical object built by the University of Iowa for the Naval Research Laboratory. It successfully obtained data on the energetic electron environment both before and after the STARFISH event. The satellite operated until December 1962 and ceased transmitting for several weeks. It then resumed transmitting for a short while and ceased again in March 1963.

Project reports make no mention of solar cell damage even though the solar cells were similar to those of other satellites reporting damage. Note that the solar cells were not covered with quartz because the electron environment was expected to be low. One possible reason for the continued operation is the relatively low current drain required by the satellite.

3.2 TRANSIT 4B

Name:	TRANSIT 4B
Active life:	November 15, 1961, to August 2, 1962
Apogee:	1110 km
Perigee:	950 km
Inclination:	32.4°
Period:	106 min

The TRANSIT 4B and TRAAC satellites were launched simultaneously into the same orbit. TRAAC was intended to be a backup satellite. The two satellites were launched and separated satisfactorily.

On June 6, 1962, prior to the STARFISH event, the RIPS power dropped to zero (Ref. 15), was intermittent for several days, and then failed completely. It was believed that the dc/dc converter failed or that the thermoelectric converter in the power unit failed.

Both the TRANSIT 4B and TRAAC satellites contained experiments to determine the performance of solar cells in the space environment. From launch to

the STARFISH event, a period of 236 days, the performace of these solar cells indicated a damage rate (approximately 17%) consistent with the knowledge of the proton flux levels. As a result of the STARFISH event, special solar panels on the TRANSIT 4B and TRAAC satellites showed a 22% decrease in output in a period of 25 days after the event. As a direct result of the decrease in power generated by the satellite's power solar cells, TRANSIT 4B ceased on August 2, 24 days after the burst.

It is interesting to note that on March 23, 1967, the TRANSIT station in Pretoria, South Africa, reported signals from TRANSIT 4B for 24 days. The satellite responded to numerous commands during April and May 1967. The frequency of the transmissions decreased and it then ceased transmitting.

3.3 TRAAC

Name:	TRAAC
Active life:	November 15, 1961, to August 12, 1962
Apogee:	1120 km
Perigee:	950 km
Inclination:	32.4°
Period:	106 min

TRAAC was launched pickaback with TRANSIT 4B into the same orbit as TRANSIT. It was intended as a backup for TRANSIT and was heavily instrumented for particle detection. TRAAC contained the first gravity stabilization system orbited. The system responded to the extension command but malfunctioned shortly thereafter.

As indicated in the discussion of TRANSIT 4B, the demise of TRAAC seems to be totally consistent with solar cell damage caused by the high-energy electron environment. The satellite stopped transmitting 36 days after STARFISH and only 12 days after the failure of TRANSIT 4B. The two satellites had solar cells with similar characteristics but of different manufacture. There is little evidence in the literature that any problems arose which could be attributed to spacecraft charging.

3.4 OSO 1 (Orbiting Solar Observatory)

Name:	OSO 1
Active life:	March 7, 1962, to August 6, 1963
Apogee:	591 km
Perigee:	550 km
Inclination:	32°
Period:	96 min

The objectives of the OSO satellite series were to perform solar physics experiments above the atmosphere during a complete solar cycle and to map the celestial sphere for direction and intensity of UV light, x rays, and gamma radiation. OSO 1 measured solar flares and subflares, monitored solar x-ray and gamma radiation, mapped the sky's gamma background, performed microscopic dust particle experiments, and measured energetic particles in the region of the lower radiation belt.

The spacecraft performed normally until the second on-board tape recorder failed on May 15, 1962, prior to STARFISH. The satellite continued to transmit real-time data over tracking stations. The STARFISH event has been held responsible for reducing the solar array output. The spacecraft provided real-time data until May 1964, when its power cells failed.

3.5 ARIEL

Name:	ARIEL
Active life:	April 26, 1962, to November 1962
Apogee:	1210 km
Perigee:	390 km
Inclination:	54°
Period:	100 min

ARIEL was a joint U.S./U.K. space research project built by NASA and carried experiments manufactured by four British universities.

ARIEL was designed to contribute to the current knowledge of the ionosphere and of the complex sun-ionosphere relationships. The satellite was a 62-kg cylinder with 58-cm diameter and 22-cm height. A tape recorder and instrumentation for five cosmic-ray measurements, two solar emission measurements, and three ionospheric experiments were on board the satellite.

Except for failure at launch of the Lyman-Alpha experiment, the spacecraft operated normally until July 9, 1967. The solar cell system used blue-sensitive p-on-n cells covered by a 0.006-inch cover glass. A feature of the power supply system was a protective undervoltage cutoff relay whereby all instrumentation except a clock was turned off whenever output voltage dropped below a specified value. There was no direct monitor of solar cell performance.

Before the STARFISH event, all satellite systems functioned normally. Within 104 hours after the explosion, the first undervoltage condition occurred, which could be explained by a reduction of 25% in solar cell efficiency. The satellite was in an undervoltage condition most of the time until August 5, 1962, a situation which was predictable from the known characteristics of the solar cells and the inferred electron environments.

However, on July 12, one day prior to the first observed undervoltage condition, there was intermittent loss of modulation both on real-time telemetry and on tape recorders. The intermittent modulation prevailed until the demise of the satellite in November. The intermittent operation could not be explained on the basis of power supply degradation alone and, in fact, was never explained. While there is certainly no direct evidence that this malfunction is due to spacecraft charging effects, it is the type of effect that might be expected.

3.6 TIROS 5

Name:	TIROS 5
Active life:	June 19, 1962, to May 1963
Apogee:	1037 km
Perigee:	630 km
Inclination:	58.1°
Period:	375 min

TIROS 5 was a weather satellite and carried medium- and wide-angle cameras. The medium-angle camera failed July 8, one day prior to the STARFISH event. The wide-angle camera continued to operate successfully for the remainder of the year. The literature gives no evidence that TIROS 5 suffered damage from the STARFISH event, but then, only a relatively small

amount of data was published for this satellite. Perhaps because of reduced power requirements resulting from payload failure, any reduction in solar array output would not have been a problem.

3.7 TELSTAR 1

Name:	TELSTAR 1
Active life:	July 10, 1962, to February 21, 1963
Apogee:	5656 km
Perigee:	955 km
Inclination:	45°
Period:	158 min

TELSTAR 1 was designed to perform communication experiments for Bell Telephone Laboratories, and it also contained experiments for measuring radiation data. It was launched one day after the STARFISH event and operated successfully for four months, with minimum difficulties reported. On August 7, one month after launch, there was an indication that one of the redundant command decoders may have been operating intermittently. By August 21, failure of one decoder appeared to be complete. However, intermittent operation of that decoder was possible for a short period in October. Then early in the week of November 18, 1962, the command system became sluggish and responded after a long string of continuous commands. The command function recovered in a limited sense in December. In January, both decoders responded to normal commands, but complete failure of the command system occurred on February 22.

A program was undertaken to determine the cause of failure. The only plausible failure mechanism suggested was ionization damage to transistors in the command decoder. This explanation does not appear to be well supported by either laboratory tests or reported experience with commands given to the satellite. A study of the available literature would lead one to the conclusion that the cause of intermittent operation was not conclusively established.

3.8 ALOUETTE

Name:	ALOUETTE
Active life:	September 29, 1962, to ?
Apogee:	1040 km
Perigee:	993 km
Inclination:	80°
Period:	105 min

ALOUETTE 1 was a small ionospheric observatory instrumented with an ionospheric sounder, a VLF receiver, an energetic particle detector, and a cosmic noise experiment. Extended from the satellite shell were two dipole antennas (45.7 and 22.8 m long, respectively) which were shared by three of the experiments on the spacecraft. The satellite was spin-stabilized at about 1.4 RPM after antenna extension. After about 500 days, the spin slowed more than had been expected, to about 0.6 RPM, when satellite spin stabilization failed. It is believed that the satellite gradually progressed toward a gravity gradient stabilization with the longer antenna pointing earthward. Attitude information was deduced only from a single magnetometer and from temperature measurements on the upper and lower heat shields. (Attitude determination may be in error by as much as 10°.) There was no tape recorder, so data were available only from the vicinity of telemetry stations. Telemetry stations were located to provide primary data coverage near the 80°W meridian plus areas near Hawaii, Singapore, Australia, Europe, and Central Africa. Initially, data were recorded for about six hours per day. In September 1972, the spacecraft was placed on standby status due to battery degradation and has since been operated occasionally to check its operating condition. There was no evidence in the literature of radiation damage or malfunction which could be attributed to spacecraft charging effects.

3.9 EXPLORER 14

Name:	EXPLORER 14
Active life:	October 2, 1962, to October 8, 1963
Apogee:	98,850 km
Perigee:	278 km
Inclination:	33°
Period:	36.6 hours

EXPLORER 14 was a spin-stabilized, solar-cell-powered spacecraft instrumented to measure cosmic-ray particles, trapped particles, solar wind protons, and magnetospheric and interplanetary magnetic fields. It was the second of the S-3 series of spacecraft, which also included EXPLORER 12, 15, and 26. A 16-channel PFM/PM time-divison multiplexed telemeter was used. The time required to sample the 16 channels (one frame period) was 0.323 sec. Half of the channels were used for analog information. The spacecraft functioned well except for the period from January 10 to 24, 1963, and after August 11, 1963, when the encoder malfunctioned, terminating the transmission of usable data. Good data were recorded for approximately 85% of the active lifetime of the spacecraft. There was no indication as to what caused the intermittent encoder malfunction.

After eight or nine orbits, the solar damage reported was:

- Unshielded p-on-n cells, 70%
- Unshielded n-on-p cells, 40%
- 3-mil shielded cells of both types, 10%

3.10 STARRAD

Name:	STARRAD
Active life:	October 26, 1962, to January 18, 1963
Apogee:	5538 km
Perigee:	193 km
Inclination:	71°
Period:	148 min

STARRAD was launched by the U.S. Air Force for the purpose of measuring electrons injected by the STARFISH event. There is no mention of spacecraft performance in the available literature. There is an oblique reference to potential problems developing in the tape recording system after the first week in orbit (Ref. 16).

3.11 EXPLORER 15

Name:	EXPLORER 15
Active life:	October 27, 1962, to February 9, 1963
Apogee:	17,300 km
Perigee:	310 km
Inclination:	18°
Period:	312 min

EXPLORER 15 was a spin-stabilized, solar-cell-powered spacecraft instrumented to study the artificial radiation belt produced by the STARFISH high-altitude nuclear burst of July 1962. The backup payload for EXPLORER 14 was modified and used for EXPLORER 15. The instrumentation included three sets of particle detectors to study both electrons and protons, and a two-axis fluxgate magnetometer to determine magnetic aspect. A 16-channel PFM/PM time-division multiplexed telemeter was used. The time required to sample the 16 channels (one frame period) was 0.323 sec. Half of the channels were used to convey eight-level digital information, and the others were used for analog information.

During launch, the spacecraft failed to despin. The spin rate ranged from 72.9 to 73.2 RPM during the life of the spacecraft. The spin axis pointed at right ascension 80.97° and declination 20.9° except for the despin failure and some other, minor, short-period encoder malfunctions. The payload functioned well from launch until January 27, 1963, when an undervoltage turnoff occurred. On recovery, the spacecraft continued to provide some data until January 30, 1963, when the second undervoltage turnoff occurred, after which time the encoder permanently malfunctioned.

Little information on the details of spacecraft operation was obtained in this effort.

3.12 ANNA 1B

Name:	ANNA 1B
Active life:	October 31, 1962, to ?
Apogee:	1250 km
Perigee:	1151 km
Inclination:	50°
Period:	107 min

No information on the operational life of the ANNA was found during the course of this effort. Apparently there were no malfunctions reported as a result of STARFISH.

3.13 INJUN 3

Name:	INJUN 3
Active life:	December 13, 1962, to November 3, 1963
Apogee:	2767 km
Perigee:	230 km
Inclination:	70°
Period:	116 min

INJUN 3 was a magnetic-field-aligned spacecraft instrumented for a study of geophysical phenomena (particularly high-altitude and auroral phenomena) using an integrated system of several particle detectors, a VLF detector, auroral photometers, and a biaxial fluxgate magnetometer. The fluxgate magnetometer was used to monitor the orientation of the spacecraft with respect to the local magnetic field. INJUN 3 had two separate telemetry and encoding systems (PCM/FSK/PM and PCM/FSK/AM) powered by a common battery-solar cell power supply. The spacecraft was launched simultaneously with and successfully separated from the U.S. Air Force spacecraft 1962 Beta Tau. INJUN 3 performed normally until late October 1963, when the satellite power supply (chemical batteries) failed. The satellite command system was partially impaired after some time in March 1963. The satellite decayed from orbit August 25, 1968.

3.14 RELAY 1

Name:	RELAY 1
Active life:	December 13, 1962, to February 1965
Apogee:	7421 km
Perigee:	1317 km
Inclination:	47°
Period:	185 min

RELAY 1 was principally a communications satellite. Included in its payload were radiation experiments designed to map the earth's radiation

4. SATELLITE ENVIRONMENTS

The primary thrust of the present effort is to determine if noticeable spacecraft charging effects occurred as a result of the artificial electron environment from STARFISH. Thus, it is important to investigate the differences between the electron environments both before and after STARFISH.

It is now thought that discharges continuously occur on the outside of a spacecraft as a result of the low-energy portion (1-20 keV) of the natural environment. Numerous discharges per day are expected. Thus, it is unlikely that the low-energy portion of the artificial environment would produce an effect on the outside of the spacecraft that is discernible from the natural effects. If the low-energy flux increased as a result of the artificial environment, the time between discharges might decrease but the basic phenomenon would remain unchanged. If the low-energy flux were to decrease as a result of the burst, the time between discharges might increase, but again, the essential phenomenon should be the same.

It appears that the energy region of most interest with respect to differences in the environment lies in the range of 40 keV up to several MeV. The flux of natural electrons is sufficiently low that the time required to charge dielectrics within the satellite behind a modicum of shielding, such as a solar array panel, is considerable. However, the fluxes of artificial electrons are significantly higher than the natural fluxes and can charge the dielectric to the point of discharging in a relatively short time. Furthermore, it is conceivable that discharges occurring within the spacecraft near unshielded cables are more likely to cause problems than discharges on the outside of the spacecraft, more remote from the cables. As a result of these considerations, only the high-energy portions of both the natural and artificial environments are here investigated.

4.1 NATURAL ENVIRONMENT

The natural electron environment in the inner zone had not been well mapped at the time of the STARFISH event, but it can be safely assumed that

belts. The spin-stabilized spacecraft had an initial spin rate of 167.3 RPM and an initial spin axis orientation with a declination of -68.3° and a right ascension of -56° shortly after launch. Two basic problems evolved. One was the satellite's response to spurious commands, and the other was the leakage of a high-power regulator. This leakage caused the first two weeks of satellite operation to be useless. After this period, satellite operation returned to normal. The leakage problem caused the spacecraft to revert to a low-voltage state early in 1965. Sporadic transmission occurred until February 10, 1965, after which no usable scientific data were obtained.

3.15 EXPLORER 16

Name:	EXPLORER 16
Active life:	December 16, 1962, to August 1963
Apogee:	1259 km
Perigee:	800 km
Inclination:	52°
Period:	104 min

The satellite payload consisted of five micrometeorite experiments. No problems were reported as a result of STARFISH.

3.16 TRANSIT 5A

Name:	TRANSIT 5A
Active life:	December 18, 1962, to December 19, 1962
Apogee:	781 km
Perigee:	742 km
Inclination:	90°
Period:	99 min

The spacecraft ceased transmission after one day due to failure in a current-limiting device. The satellite's batteries overcharged, causing power system failure.

the environment is very similar to what it is today. Again, while there were several high-altitude tests prior to July 9, 1962 (see Table 1), it is unlikely that they had caused a large perturbation in the environment in the months preceding July 9. These bursts were either at relatively low altitudes or of low yield such that the magnitude of the initial perturbation was small, and the artificial electron lifetimes were short.

As a result, the current models for the inner zone environments should be sufficiently accurate for this study. The natural environments for five satellite orbits of interest have been computed by Radke (Ref. 17) using the AE5 environments. The electron flux averaged over two days is shown in Figure 2 for the July 1962 time frame, corresponding to the conditions of a solar minimum.

4.2 NUCLEAR ENVIRONMENT

The magnitude and spectrum of the artificial environment are a strong function of burst location, time after burst, and location in space. Numerous on-board measurements on satellites in orbit at the time of STARFISH can be used to gain insight into artificial environment encountered by the various satellites.

It is thought that the spectrum of the artificial environment resembles a fission spectrum, as shown in Figure 3. The flux is a strong function of time after burst and of location. Based on available satellite data, Hess (Ref. 18) has computed the average daily electron fluxes that would have been encountered by several low-altitude satellites during the first few days. These results are summarized in Table 3; it is evident that the average fluxes are on the order of 10^{12} to 10^{13} e/cm^2/day.

4.3 COMPARISON OF NATURAL AND NUCLEAR ENVIRONMENTS

The cumulative natural and nuclear electron fluences for several satellites are shown as a function of energy in Figure 4. The lower artificial level corresponds to that computed for ARIEL, while the upper artificial level corresponds to that for TELSTAR.

The difference between the natural and artificial environments for a given satellite represents the increased average flux that the satellites would have encountered in the first several weeks after the burst.

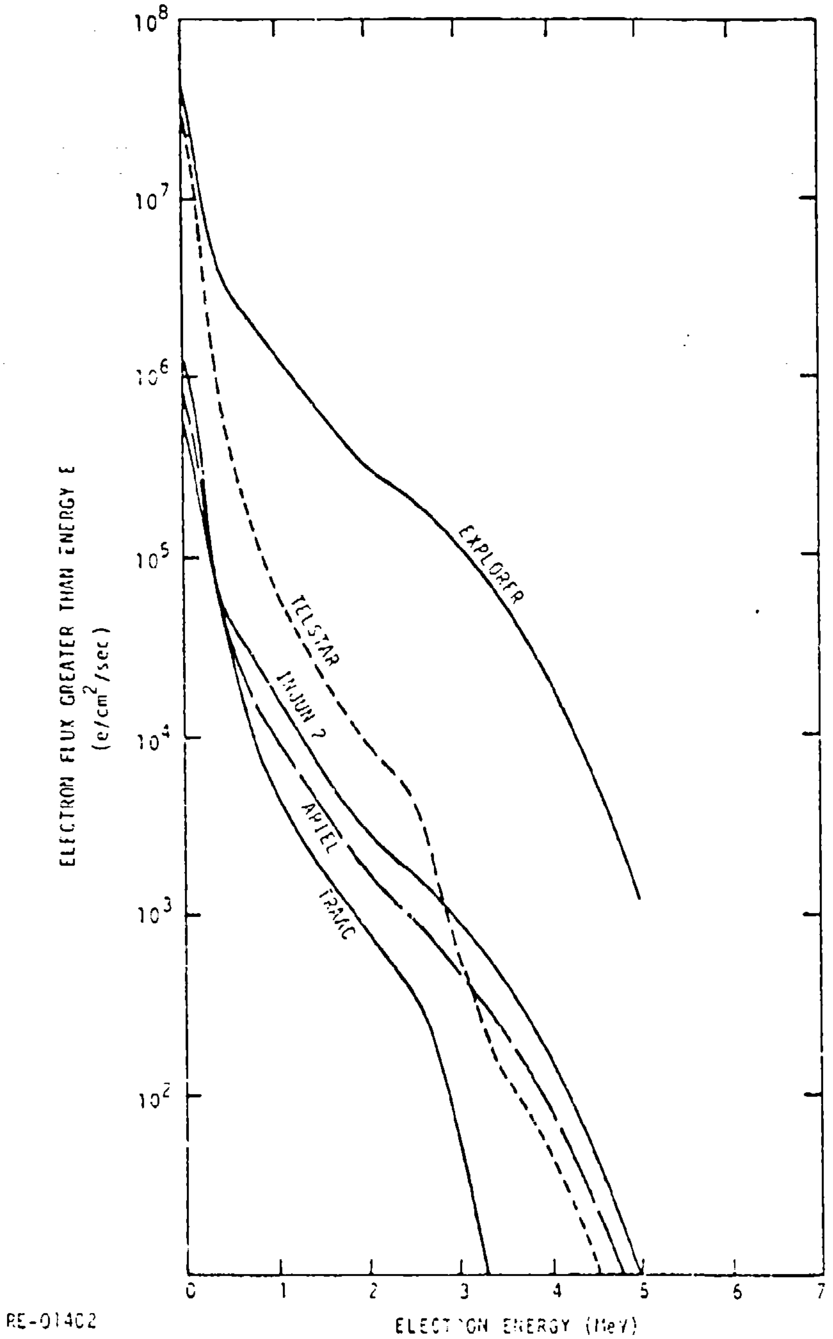
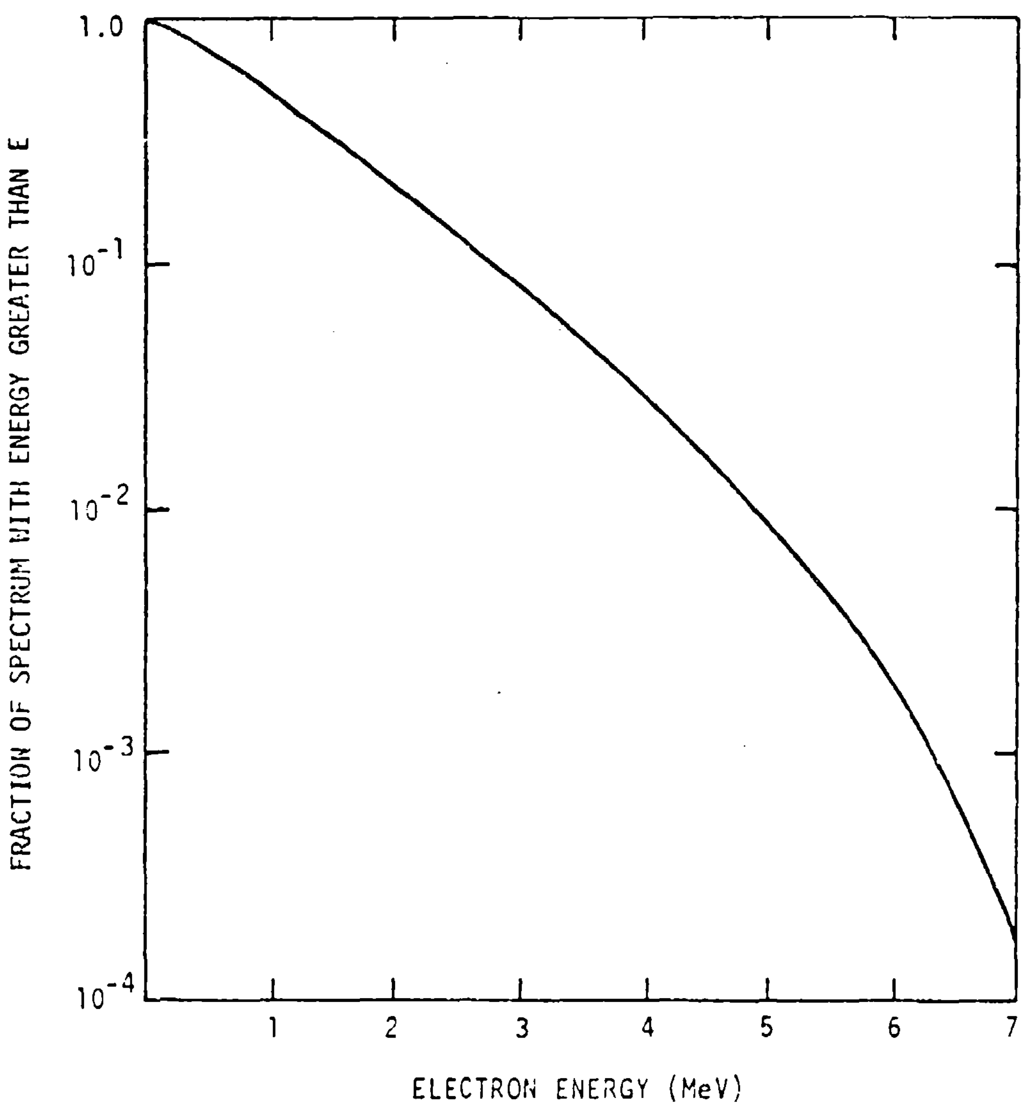


Figure 2. Integral natural electron flux for energies greater than 40 keV for five satellites prior to STARFISH (July 1962)

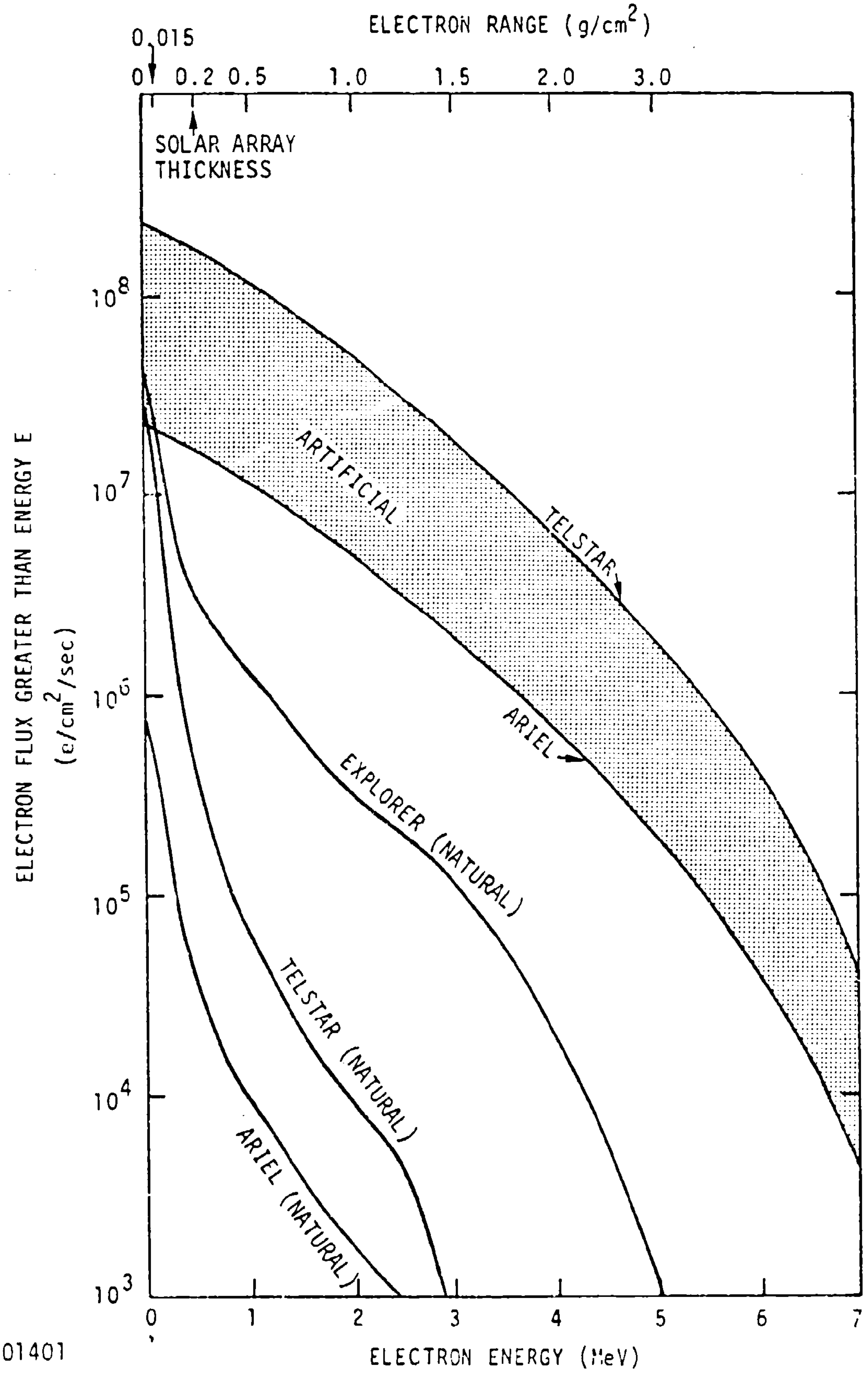


RE-01403

Figure 3. Typical integral fission spectrum

Table 3. Calculations of Fluxes Encountered by Satellites Moving through the Artificial Radiation Belt (Ref. 18)

Vehicle	ARIEL	TRAAC and TRANSIT 4B	TELSTAR	TIROS 5	OSO 1	RELAY
Perigee (km)	390	960	952	590	552	1343
Apogee (km)	1210	1106	5660	971	594	5555
Inclination (°)	54	32	45	58	33	50
Altitude (km)						
30°S lat.	1067	1000	5138	963	594	4371
30°W long.			1758			
Calculated R/day outside vehicle	110,000	180,000	800,000	46,000	27,000	1.1×10^8
Length of machine run in satellite days	4	4	4	4	4	4
$e/cm^2/day$	2.8×10^{12}	4.5×10^{12}	2.0×10^{13}	1.15×10^{12}	6.8×10^{11}	2.7×10^{13}



RE-01401

Figure 4. Natural and artificial electron environments for several satellites, showing cumulative spectra above 40 keV

It is of some interest to estimate the difference in flux behind various shield thicknesses. Such an estimate can readily be made by using the electron range-energy relationship. The equivalent electron ranges in g/cm^2 are indicated at the top of Figure 4. It is evident that the artificial environment produces a vastly increased flux of electrons within the satellite. For example, the total flux behind a solar array would have been 3.5×10^4 $e/cm^2/sec$ before the burst and 1.8×10^7 $e/cm^2/sec$ after the burst. A summary of the fluxes before and after STARFISH is given in Table 4.

Table 4. Electron Fluxes Before and After STARFISH

	Incident Flux ($e/cm^2/sec$)			Flux Behind 0.2 g/cm^2 ($e/cm^2 sec$)		
Satellite	Natural	Nuclear	Ratio	Natural	Nuclear	Ratio
ARIEL	8.0×10^5	3.2×10^7	40	3.2×10^4	2.5×10^7	780
TRAAC	1.2×10^6	5.2×10^7	43	3.1×10^4	4.1×10^7	1300
TELSTAR	2.8×10^7	2.3×10^8	8	3.9×10^5	1.8×10^8	460

5. SPACECRAFT CHARGING EFFECTS

As discussed in Section 4, the most likely discernible effects caused by the artificial environment, if any, will occur as a result of dielectric charging within the spacecraft. For the higher-energy electrons required to penetrate spacecraft skins, the flux of natural electrons is relatively low, while the flux of artificial electrons is relatively high. Furthermore, discharges within the spacecraft itself are more likely to cause problems because they occur closer to cables leading directly to electronics and, therefore, can couple discharge signals more efficiently.

There are several possibilities with respect to charging and discharging within the spacecraft. First there is a possibility that discharges occur between large isolated conductors on the spacecraft. There is no evidence in the literature that indicates the satellites of interest were constructed with large isolated conductors, although the possibility cannot be ruled out.

A second possibility is that dielectrics charge until a discharge occurs, at which time either surface flashover or bulk breakdown occurs. The satellites of interest were constructed with large sheets of fiberglass material ranging in thickness from 1/32 to 1/16 inch, and other dielectrics such as cable insulation and thermal blanket materials. Recent experiments (Ref. 19) with relatively high fluxes (nA/cm^2) of high-energy electrons ($\sim$1 MeV) indicate that surface discharges on fiberglass and teflon dielectrics will occur when the accumulated surface charge density exceeds 10^{-7} C/cm^2. Thus, it appears highly likely that discharges of this type could occur whenever current densities of 10^{-7} C/cm^2 or greater are incident on dielectrics in a relatively short time (less than the relaxation time of the dielectric).

Finally, there is the possibility that charge accumulating in the dielectric will leak off at the same rate it accumulates, such that an equilibrium is established at a level below the breakdown threshold. This will occur only if (1) the incident electron flux is so low that the time required to accumulate charge densities required for discharges is longer than the relaxation time, or (2) the radiation-induced conductivity of the dielectric is sufficiently high to permit relaxation.

There is substantial evidence that dielectrics exposed to electron beams will discharge when the accumulated charge reaches 10^{-7} C/cm^2, and that the charge does not leak off fast enough through conduction processes. The charging and discharging estimates in the remainder of this chapter are made with the assumption that the dielectrics in the spacecraft of interest could discharge if exposed to charge densities in excess of 10^{-7} C/cm^2.

5.1 CHARGING RATES

Estimates of charging and discharge effects are made by using a 10-mil fiberglass face sheet as a representative spacecraft dielectric. Two cases are considered, one in which the dielectric is directly exposed to the natural and artificial environments separately, and one in which the dielectric is located behind 0.2 g/cm^2 of low-Z material such as a solar array. The resulting current densities, fractions of the incident spectra stopped in the dielectric, surface charge densities just prior to breakdown, and times required to charge to breakdown have been computed for environments corresponding to ARIEL and TELSTAR. The fraction of charge stopping in the dielectric was estimated from the environments shown in Figure 4, using the following expression for Δf.

$$\Delta f = \frac{1}{J} \frac{dJ}{dE} \frac{dE}{dx} \Delta x \ , \tag{10}$$

where dE/dx is the electron stopping power for electrons of energy E stopping in the 10-mil slab and Δx is the slab thickness. Equations 3 and 6 were used to estimate the surface charge density just prior to breakdown and the time required for breakdown. Results of these calculations are summarized in Tables 5 and 6 for ARIEL and TELSTAR. The results for the dielectric located at the surface, exposed directly to the environment, are included only to show the contributions of the high-energy portions of the spectra to the charging. In reality, charging at the spacecraft outer surface will be most likely dominated by the low-energy portion of the environment not considered here. Thus, the time required to charge to breakdown on the outside of the satellite will be less than the time indicated in the tables.

Table 5. ARIEL Satellite

Quantity	Surface		Behind 0.2 g/cm^2	
	Natural	Artificial	Natural	Artificial
Current density, J (amp/cm^2)	1.2×10^{-13}	5.9×10^{-12}	4.8×10^{-15}	4×10^{-12}
Fractions of charge stopped, Δf	0.3	0.04	0.13	0.04
Surface charge density threshold, σ_B (C/cm^2)	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Time to discharge, t (sec)	5.5×10^{6} (64 days)	8.5×10^{5} (9.8 days)	3.2×10^{8} (3.7×10^{3} days)	1.2×10^{6} (14 days)

Table 6. TELSTAR Satellite

Quantity	Surface		Behind 0.2 g/cm^2	
	Natural	Artificial	Natural	Artificial
Current density, J (amp/cm^2)	4.8×10^{-12}	3.7×10^{-11}	6.4×10^{-14}	2.9×10^{-11}
Fraction of charge stopped, Δf	0.26	0.04	0.2	0.04
Surface charge density threshold, σ_B (C/cm^2)	2×10^{-17}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Time to discharge, t (sec)	1.6×10^{5} (1.8 days)	1.3×10^{5} (1.5 days)	1.6×10^{7} (185 days)	1.7×10^{5} (1.9 days)

The most interesting results are for the dielectrics shielded by a small thickness of the spacecraft skin. Note that the electron fluxes behind 0.2 g/cm^2 of low-Z material due to the artificial environment are 500 to 1000 times higher than for the natural environment. The time required for the artificial environment to charge the dielectric to the point of breakdown is on the order of 2 to 14 days, while the corresponding time required for the natural environment would be 0.5 to 1 year, assuming the charge would not relax in that time.

It is evident that the artificial environment can cause substantially increased charging rates within typical satellite structures; therefore, it is plausible that the artificial environment would cause discharges within the spacecraft several days to weeks after the burst, while the natural environment might not cause similar discharges for extremely long periods of time after launch. Thus, if a particular spacecraft were sensitive to discharges occurring within the structure itself, it is possible that the STARFISH event could have caused discernible effects that would not have been caused by the natural environment.

5.2 RESPONSE MAGNITUDES

It is of interest to estimate the magnitudes of discharge currents and the resulting signals which might be induced with spacecraft structures and cables. To estimate these responses, it is necessary to guess how much area might be involved in the discharge and estimate the discharge current pulse width. Experiments (Refs. 20,21) have indicated that at least 10^3 cm^2 can be involved in a single discharge of the surface, and that typical pulse widths are on the order of 100 nsec. Using these values for area and pulse width, the discharge currents I_D according to Equation 4 are

$$I_D = \frac{\sigma A}{\Delta t} = 2000 \text{ amp} \ .$$

The current flowing in a structure some distance from the satellite is diminished by the ratio of dielectric thickness to structural characteristic dimension. A typical dielectric thickness of 1/16 inch found on the ARIEL satellite with an overall cavity dimension of 20 inches results in a structural replacement current I_S on the order of

$$I_S = I_D \frac{d}{R} = 2000 \times \frac{1/16}{20} = 6 \text{ amp} .$$

These currents are sufficiently large to be of concern for upset and/or burn-out, particularly for satellites with unshielded cables. Thus, it is at least conceivable that the STARFISH event could have produce significant effects on spacecraft in orbit before and within the few months following the event.

6. DISCUSSION AND SUMMARY

The purpose of this study is to determine whether the artificial electron environment produced by the STARFISH event caused any discernible spacecraft charging effects on satellite operation prior to or immediately after the burst. Even before commencing the study, it was evident that determining a definite cause-effect relationship between discharges and anomalous behavior would be virtually impossible. Even today, when spacecraft charging effects are recognized, it is difficult to sort out the causes of satellite anomalies. At the time of the STARFISH event, spacecraft charging was not recognized as a problem, and many of the clues which might have helped to determine if spacecraft charging was occurring were probably not recorded.

Therefore, at best one could only hope to piece together circumstantial evidence that:

1. Given the known environments and spacecraft configurations, spacecraft charging and discharging could have, and/or were likely to have, occurred as a result of STARFISH, and
2. Satellite operation and malfunctions following STARFISH were characteristic of those which could be expected from spacecraft charging effects (e.g., erratic operation or sudden and complete malfunction as opposed to slow continuous degradation characteristic of solar cell damage).

Such circumstantial evidence has been gathered, as indicated in Sections 2 through 5, and is summarized below.

6.1 PLAUSIBILITY OF DISCHARGE PRODUCED BY STARFISH

It is quite likely that discharges were occurring on the external surface of the satellites even prior to the STARFISH event as a result of the low-energy portion of the natural environment. Such discharges seem to be routinely occurring on spacecraft in orbit today (Ref. 6). Thus, it is unlikely that the STARFISH event produced any distinguishable spacecraft charging effects on the outside of the spacecraft.

However, the fluxes of high-energy electrons in the natural environment were sufficiently low that no discharges would have occurred within the satellite behind relatively thin layers of the outer satellite skin. STARFISH produced significant fluxes of high-energy electrons which could have charged dielectrics to the point of discharge within days to weeks after the event, depending on the orbit. Furthermore, recent experimental evidence (Refs. 19, 20) indicates that dielectric materials similar to those found aboard spacecraft of interest will discharge when exposed to greater than 10^{-7} C/cm^2 of high-energy electrons.

Given that discharges did occur, there still remains the question of whether the discharges would have been sufficiently large to produce malfunctions. Estimates of discharge responses indicate that currents on the order of 6 amp could have been coupled into structures such as cables. Although malfunction thresholds are not known for the satellites in question, 6 amp on a cable is sufficient to produce malfunctions in many types of circuits. This issue can best be addressed, however, by considering current satellites. It is now thought that spacecraft charging effects are responsible for numerous anomalies that occur on virtually all spacecraft (Refs. 6,22). It is also thought that the demise of at least one spacecraft (Ref. 5) was due to spacecraft charging effects. Thus, it must be concluded that spacecraft charging effects can be sufficiently severe to cause anomalous operation of some satellites.

The evidence is strong that STARFISH produced an environment which quite likely caused discharges within the spacecraft, whereas the natural environment did not. Furthermore, it is known that spacecraft charging can cause satellite malfunctions. Thus, for a satellite which was relatively insensitive to discharges on the exterior surface but sensitive to discharges within the spacecraft itself, STARFISH could have produced discernible effects on satellite operation.

6.2 SPACECRAFT ANOMALIES CAUSED BY STARFISH

Available literature was reviewed to determine the operation of all satellites immediately before and after STARFISH. An attempt was made to distinguish between malfunctions which could be directly traced to long-term

ionization problems, such as damage to solar arrays, and those which were singular, erratic, or unexplainable and which might be characteristic of spacecraft charging effects.

Following is a summary of the reported operation of the satellites, listed in Table 2, immediately after the STARFISH event.

1. There were at least three satellites — TRAAC, TRANSIT 4B, and ARIEL — whose early demise can be directly related to long-term ionization (total dose) problems in the solar arrays resulting from the artificial electron environment produced by STARFISH. These satellites contained on-board experiments that monitored solar cell efficiencies as well as the high-energy environment. There is reason to believe that the active lives of two other satellites — OSO 1 and RELAY 1 — were also shortened due to solar cell degradation.
2. At least four satellites experienced anomalous and erratic behavior which may or may not have been caused by long-term ionization problems. These satellites include TELSTAR 1, EXPLORER 14, EXPLORER 15, and RELAY 1.
3. In at least one satellite, ARIEL, anomalous and erratic operation could not be explained on the basis of total-dose problems (Ref. 23). ARIEL operated normally from launch ten weeks prior to STARFISH until two days after the event. At this time, anomalous malfunctions occurred and continued to occur until the end of its active life, four months after STARFISH. The anomalous operation occurred prior to any undervoltage condition from solar cell degradation, and was never explained. The satellite eventually failed as a result of solar cell degradation.
4. There are numerous other satellites for which no serious malfunction resulting from STARFISH was reported, including the INJUN 1, TIROS 5, ALOUETTE, STARRAD, ANNA 1B, INJUN 3, and TRANSIT 5A. Several possibilities exist with respect to these satellites. First, there may have been problems not reported in the literature reviewed. Second, malfunctions not related to STARFISH may have shortened the life of the satellite before

any long-term ionization or other STARFISH-related effects caused problems. Finally, there may, in fact, have been no problems resulting from STARFISH.

It is quite evident that anomalous operation of several satellites occurred as a result of STARFISH. Much of this anomalous operation can be directly blamed on undervoltage conditions caused by solar cell degradation. However, it is clear that not all anomalous operation can be blamed on undervoltage conditions or on long-term ionization in other components. It also is clear that there is absolutely no way to determine whether the anomalies are a result of spacecraft charging and discharging, even if one assumes that discharges were occurring.

6.3 SUMMARY

No direct evidence was found in this study that any anomalous satellite operation resulted from spacecraft charging effects caused by STARFISH. However, there is sufficient circumstantial evidence to indicate that spacecraft charging effects could have occurred. First, it has been determined that satellites of interest were exposed to sufficient fluxes of energetic electrons as a result of STARFISH to produce discharges within the spacecraft, whereas the fluxes of energetic electrons in the natural environment would have been insufficient to cause such discharges. Second, it has been demonstrated experimentally that dielectrics similar to those on spacecraft of interest have discharged when exposed to energetic (MeV) electrons with electron fluences equivalent to those accumulated by dielectrics within spacecraft exposed to the STARFISH environment for periods of several days to several weeks. Third, it is known that discharges can produce anomalous satellite responses, and in fact, at least one spacecraft failure is attributable directly to spacecraft charging effects. Finally, anomalous behavior was reported on several satellites shortely after STARFISH that could not be attributed to long-term ionization effects, the effects which are generally thought to be responsible for the early demise of at least three or four satellites. This anomalous behavior was never satisfactorily explained.

Further information on the type and frequency of malfunctions arising from STARFISH might be obtained by investigating records of spacecraft operation immediately following STARFISH. Candidate spacecraft of particular interest are ARIEL, RELAY 1, TELSTAR 1, and EXPLORER 14 and 15. Records of the telemetry of some of these satellites might be obtained from the Space Data Center at Goddard Space Flight Center.

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